

# **$K_S$ semileptonic decays and test of $\mathcal{CPT}$ symmetry with the KLOE detector**

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Study of semileptonic decays of neutral kaons allows to perform a test of discrete symmetries, as well as basic principles of the Standard Model. In this paper a general review on dependency between charge asymmetry constructed for semileptonic decays of short- and long-lived kaons and  $\mathcal{CPT}$  symmetry is given.

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## 1. Introduction

Investigations of the neutral kaon system, due to the system's sensitivity to a variety of discrete symmetries such as charge conjugation ( $\mathcal{C}$ ), parity ( $\mathcal{P}$ ) and time reversal ( $\mathcal{T}$ ), allow to test the  $\mathcal{CPT}$  symmetry as well as basic principles of the Standard Model. Specifically, this paper focuses on the difference and sum of charge asymmetries for the short-lived kaon ( $A_S$ ) and the long-lived kaon ( $A_L$ ) to search for  $\mathcal{CPT}$  symmetry violation.

## 2. Charge asymmetry in semileptonic decays of $K_S$ meson

Short- and long-lived kaon states, which are hamiltonian eigenvalues, are mixture of states  $K^0$  and  $\bar{K}^0$  [1]:

$$|K_{L/S}\rangle = \frac{1}{\sqrt{2(1 + |\epsilon_{L/S}|^2)}} \left( (1 + \epsilon_L) |K^0\rangle \mp (1 - \epsilon_{L/S}) |\bar{K}^0\rangle \right), \quad (1)$$

where the parameters  $\epsilon_L$  and  $\epsilon_S$  account for  $\mathcal{CP}$  and  $\mathcal{CPT}$  symmetries violation. These parameters can be expressed in terms of  $\epsilon_K$  and  $\delta_K$  describing

(1)

$\mathcal{CP}$  and  $\mathcal{CPT}$  symmetries violation, respectively:

$$\epsilon_{L/S} = \epsilon_K \mp \delta_K. \quad (2)$$

In order to describe semileptonic kaon decays ( $K \rightarrow \pi e \nu$ ), due to Eq. 1, only the following decay amplitudes should be taken into account:

$$\begin{aligned} \langle \pi^- e^+ \nu | H_{weak} | K^0 \rangle &= \mathcal{A}_+, & \langle \pi^+ e^- \bar{\nu} | H_{weak} | \bar{K}^0 \rangle &= \bar{\mathcal{A}}_-, \\ \langle \pi^+ e^- \bar{\nu} | H_{weak} | K^0 \rangle &= \mathcal{A}_-, & \langle \pi^- e^+ \nu | H_{weak} | \bar{K}^0 \rangle &= \bar{\mathcal{A}}_+, \end{aligned} \quad (3)$$

where the  $H_{weak}$  is the term of Hamiltonian corresponding to the weak interaction and  $\mathcal{A}_+, \bar{\mathcal{A}}_-, \mathcal{A}_-, \bar{\mathcal{A}}_+$  parametrize the semileptonic decay amplitudes. According to the Standard Model, decay of  $K^0$  (or  $\bar{K}^0$ ) state is associated with the transition of the  $\bar{s}$  quark into  $\bar{u}$  quark (or  $s$  into  $u$ ) and emission of the charged boson. Change of strangeness ( $\Delta S$ ) implies the corresponding change of electric charge ( $\Delta Q$ ). This is so called  $\Delta S = \Delta Q$  rule. Therefore, decay of  $K^0 \rightarrow \pi^- e^+ \nu$  and  $K^0 \rightarrow \pi^+ e^- \bar{\nu}$  are present but  $K^0 \rightarrow \pi^+ e^- \bar{\nu}$  and  $\bar{K}^0 \rightarrow \pi^- e^+ \nu$  are not. This implies that, if  $\Delta S = \Delta Q$  rule is conserved then parameters  $\mathcal{A}_-$  and  $\bar{\mathcal{A}}_+$  vanish.

For further consideration it is useful to introduce the following notations:

$$\begin{aligned} x &= \frac{\bar{\mathcal{A}}_+}{\mathcal{A}_+}, & \bar{x} &= \left( \frac{\mathcal{A}_-}{\bar{\mathcal{A}}_-} \right)^*, & y &= \frac{\bar{\mathcal{A}}_-^* - \mathcal{A}_+}{\bar{\mathcal{A}}_-^* + \mathcal{A}_+}, \\ x_{\pm} &= \frac{x \pm \bar{x}^*}{2} = \frac{1}{2} \left[ \frac{\bar{\mathcal{A}}_+}{\mathcal{A}_+} \pm \left( \frac{\mathcal{A}_-}{\bar{\mathcal{A}}_-} \right)^* \right]. \end{aligned} \quad (4)$$

By applying symmetry operators to amplitude of zero-spin system, relations between parameters introduced in Eq. 4 and conservation of a particular symmetry [1] can be obtained. Those relations are summarized in Table 1.

Conserved quantity	Required relation
$\Delta S = \Delta Q$ rule	$x = \bar{x} = 0$
$\mathcal{CPT}$ symmetry	$x = \bar{x}^*, y = 0$
$\mathcal{CP}$ symmetry	$x = \bar{x}, y = \text{imaginary}$
$\mathcal{T}$ symmetry	$y = \text{real}$

Table 1. Relations between discrete symmetries and semileptonic amplitudes

Quantities from Eq. 4 can be associated to the  $K_S$  and  $K_L$  semileptonic decay widths through the charge asymmetry ( $A_{S,L}$ ):

$$\begin{aligned} A_{S,L} &= \frac{\Gamma(K_{S,L} \rightarrow \pi^- e^+ \nu) - \Gamma(K_{S,L} \rightarrow \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \rightarrow \pi^- e^+ \nu) + \Gamma(K_{S,L} \rightarrow \pi^+ e^- \bar{\nu})} \\ &= 2 [Re(\epsilon_{S,L}) - Re(y) \pm Re(x_-)]. \end{aligned} \quad (5)$$

The above equation contains only the first order of symmetry-conserving terms with parameters  $\epsilon_S$ ,  $\epsilon_L$  which can be expressed in terms of the  $\mathcal{CP}$  and  $\mathcal{CPT}$  violation parameters  $\epsilon_K$  and  $\delta_K$ .

Sum and difference of the  $A_S$  and  $A_L$  allow to search for the  $\mathcal{CPT}$  symmetry violation, either in the decay amplitudes through the parameter  $y$  (see Table 1) or in the mass matrix through the parameter  $\delta_K$ :

$$\begin{aligned} A_S + A_L &= 4\text{Re}(\epsilon) - 4\text{Re}(y), \\ A_S - A_L &= 4\text{Re}(\delta_K) + 4\text{Re}(x_-). \end{aligned} \quad (6)$$

A precise measurement of the number of  $K_S$  and  $K_L$  semileptonic decays allows to determine the value of charge asymmetry and tests  $\mathcal{CPT}$  violation and  $\Delta S = \Delta Q$  rule violation. The charge asymmetry for long- and short-lived kaons were determined by CPLEAR and KLOE experiments, respectively [2, 3]. Measurement of  $A_L$  was based on 1.9 millions  $K_L \rightarrow \pi e \nu$  decays produced in collisions of proton beam with a BeO target. Following values were obtained [3]:

$$A_L = (3.322 \pm 0.058_{\text{stat}} \pm 0.047_{\text{syst}}) \times 10^{-3}. \quad (7)$$

At present most accurate measurement of  $A_S$  was performed with  $0.41 \text{ fb}^{-1}$  total luminosity data sample and is equal [2]:

$$A_S = (1.5 \pm 9.6_{\text{stat}} \pm 2.9_{\text{syst}}) \times 10^{-3}. \quad (8)$$

This result is consistent with the charge asymmetry determined for long-lived kaons within errors.

### 3. Measurement

Obtained results of  $A_S$  and real part of  $x_+$ ,  $x_-$ ,  $y$  parameters allow to perform the most precise tests of  $\mathcal{CPT}$  symmetry and  $\Delta S = \Delta Q$  rule in semileptonic decays of neutral kaons. However, accuracy on  $A_L$  determination is more than two orders of magnitude bigger than this of the  $A_S$  and the uncertainty on  $A_S$  is dominated by the data sample statistics three times larger than the systematic contribution.

#### 3.1. KLOE

The measurement is based on the ability to tag a  $K_S$  meson by identifying the  $K_L$  meson. The KLOE detector consists of two main parts: a drift chamber [4] and a barrel shaped electromagnetic calorimeter [5], both inserted into a magnetic field (0.52 T). Around 60% of  $K_L$  mesons reach the electromagnetic calorimeter and can be identified by their energy deposition

inside it. The selection of  $K_S \rightarrow \pi e \nu$  decays requires a vertex reconstructed near the Interaction Point with two tracks that belong to two oppositely charged particles. These particles must reach the calorimeter and deposit energy inside it in order to use Time of Flight technique. This technique aims at rejecting background, which consists mainly of  $K_S \rightarrow \pi \pi$  events, and at identifying the final charged states ( $\pi^+ e^- \bar{\nu}$  and  $\pi^- e^+ \nu$ ). The distribution of the difference between missing energy and momentum ( $\Delta E(\pi, e)$ ) shows the remaining background components (see Figure 3.1). Based on an integrated luminosity of  $1.7\text{fb}^{-1}$  around  $10^5$  of  $K_S \rightarrow \pi e \nu$  decays were reconstructed and will be used to determine the charge asymmetry and branching ratio for  $K_S$  semileptonic decays. A preliminary analysis shows a potential of reaching a two times better statistical error determination with a sample four times bigger than the previous KLOE analysis. The analysis is still in progress and preliminary results will be available soon.

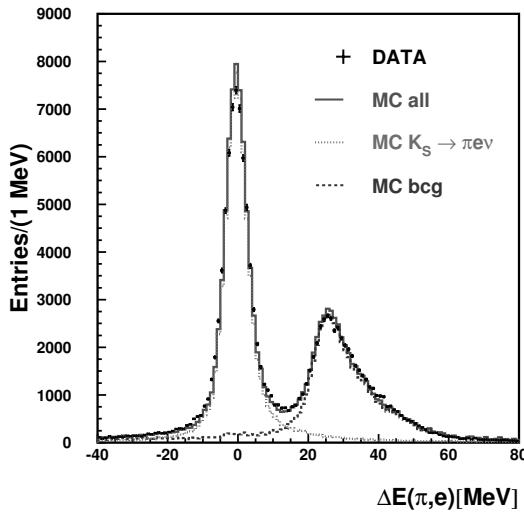


Fig. 1. Distribution of  $\Delta E(\pi, e) = E_{miss} - p_{miss}$  for all selected events after normalization procedure.

### 3.2. Prospects for KLOE-2

In the near future further improvements of both statistical and systematical uncertainty are expected thanks to the luminosity upgrade of DAΦNE and the installation of new sub-detectors in the KLOE-2 experiment [6]. The improvement on kaon vertex reconstruction and acceptance for tracks with low transverse momentum in the region near the Interaction Point crucial for  $K_S$  decays, will be ensured by the newly installed Inner Tracker sub-detector [7]. KLOE-2 is also equipped with low- and high- energy taggers that allow to identify  $e^+e^-$  originated from  $e^+e^- \rightarrow e^+e^-X$  reactions for  $\gamma\gamma$  physics [8, 9]. Reconstruction of neutral particles at low polar angles will be improved due to the installation of CCALT [10] and QCALT [11] extra calorimeters. It should be emphasised that KLOE-2 aims to significantly improve the sensitivity of tests of discrete symmetries, through studies of  $K_S$  charge asymmetry or quantum interferometry effects in the kaon decays, beyond the presently achieved results [6, 12].

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